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ScienceDirect
Physics Procedia 19 (2011) 88–95
Physics Procedia

International Conference on Optics in Precision Engineering and Nanotechnology

A palm-top camera for 3D profilometry using a single MEMS mirror

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Abstract

To realize a compact three-dimensional profile measurement system that is based on pattern projection method, we have proposed incorporating a recent digital device such as a MEMS scanner into projection optics. Due to this revision, first of all, such a small size system like a palm-top camera became attainable, and low cost measurement system has been potentially realized. In this system, we control a single MEMS scanner to produce the projection pattern with appropriate periodical structure and sinusoidal intensity distribution. Due to this flexibility in pattern projection, such a compact camera as a palm-top size is attainable. We adopted phase-shifting technique which is most popular technique applicable to profile measurement and inspection in automobile industry and others. This camera will be potentially as small as a photographic digital camera in dimensional size. In addition, we propose to use RGB color projection system to make up for the shortcomings such as short depth of field inherent to conventional systems and, at the same time, we aim to attain higher speed of measurement.

Keywords: Profilometry, Three dimensional shape measurement, pattern projection method, MEMS scanner;

1. INTRODUCTION

Until now, a lot of researchers have proposed principles for three-dimensional measurement using the pattern projection method. There seemed that no further discussion is necessary for the fundamental principle concerning the pattern projection method. However, the pattern projection method has attracted attention in recent years, again. [1)]. One of the trigger is that we can easily get a DLP projector with a DMD (Digital Mirror Device). Actually, a lot of researchers have proposed three dimensional measurement systems with the help of a projector incorporating the DMD[2)]. The most of all every systems use the DMD made by Texas Instruments Inc.. The DMD have been aligned micro-mirrors on the plane like a matrix. Against to the method incorporating the type of aligned micro-mirrors as the DMD, we have proposed the projection technique based on a single MEMS mirror[3,4)].

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doi:10.1016/j.phpro.2011.06.130

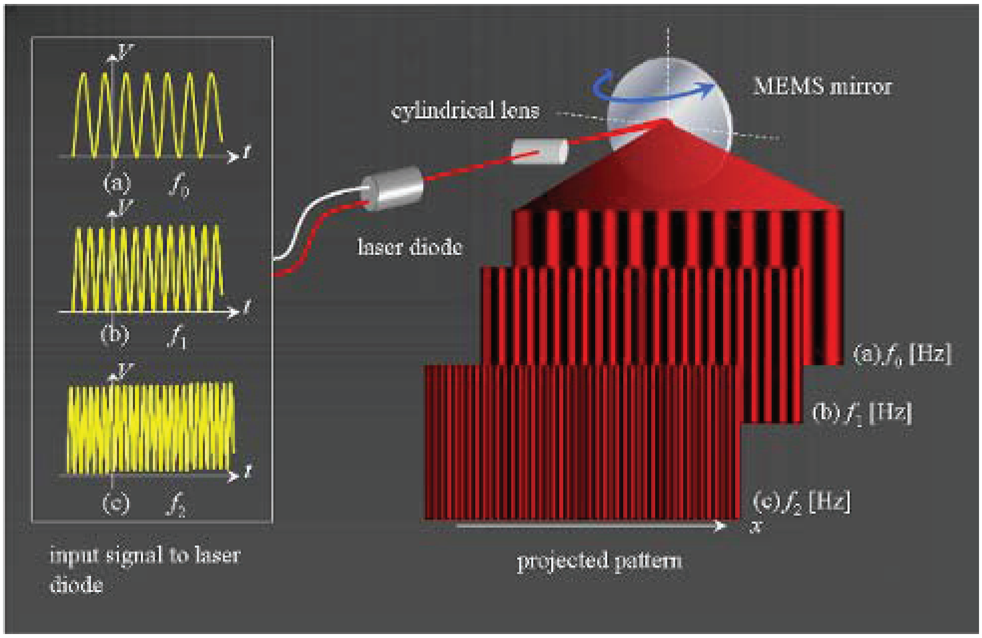


Fig.1 MEMS projection technique with different periodical patterns

Moreover, we have proposed a real-time measurement method of 3D profile using 3CCD camera and 3 color laser diodes such as red, green and blue[5)].

When we advance our research work concerning a palm-top camera for 3D profilometry, news of "car-recall" got quickly around the all over the world[6)]. The recall issue concerns about an accelerator pedal getting stuck on floor mats. Japanese car maker recalled 1.1 million more cars in the US. With this news as a trigger, Japanese car maker have strongly recognized to inspect even small parts using three-dimensional measurement. However, conventional three-dimensional measurement system is very large, very heavy and very expensive. From this background, a palm-top camera for 3D profilometry has been strongly requested. The requirements to 3D measurement system from Japanese car maker are small size like a digital camera, its weight, possible to mobile, finally, not expensive under three hundred thousand US dollars. From this background, our palm-top camera for 3D measurement has developed for the evaluation of automobile parts[4,5)]. In addition to the requirement of carmaker, there is now growing the requirement concerning the palm-top camera for 3D measurement. The requirements cover various fields from the inspection and the designing of the products to the amusement application.

In this paper, we aim at achieving a wide range measurement for a height. For this purpose, we try to illuminate different periodical patterns with a phase shifting algorism. According to different periodical patterns, we can measure even a special sample with large steps.

2. PRINCIPLE

Figure 1 shows the MEMS projection technique with different periodical patterns. We employed a laser diode with monochromatic light source. The laser beam is expanded by a cylindrical lens from a point beam to a line beam. The line beam is incident into a single MEMS mirror. The line beam can transform to the illumination of two-dimensional surface. The projection pattern is formed by modulating the voltage of the laser diode, sinusoidally. That is to say, we can generate the projection pattern with appropriate periodical structures and the sinusoidal intensity distribution transformed from a time domain to a spatial domain. In this case, the phase of projected fringe pattern can be controlled by initial phase of input signal, electrically. Moreover, the period of projected fringe pattern can modulate by the frequency of input signal as shown in Fig 1(a), (b) and (c). We can fast control the period of the projected pattern with electrical signals by a functional generator.

Figure 2 shows the optical configuration of a palm-top camera for 3D profilometry incorporating a single MEMS mirror[7)]. The single MEMS mirror as a projector is located at the point A(0, b, a) in Fig.2. A lens of CCD camera is set at the point B(0, 0, a). The CCD is dislocated the displacement c to z direction from the point B and the point P

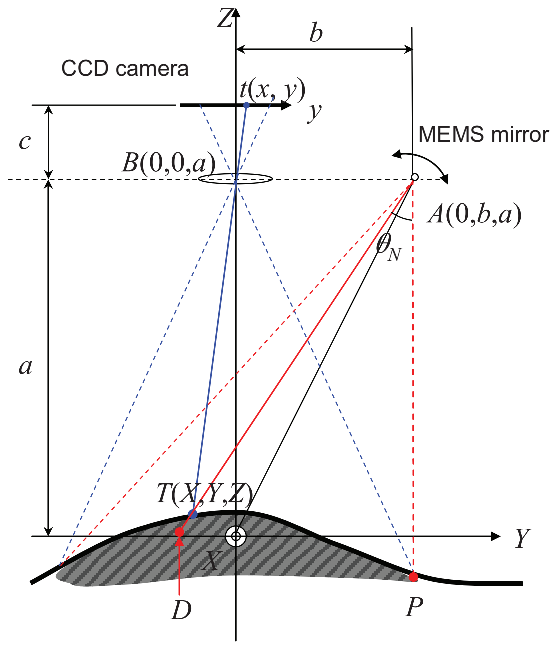


Fig.2 Optical configuration of three- dimensional profilometry

is located at (0, b,0). The base line between the CCD camera and the projector is a length b. The angle θ_N gives ∠ PAT. The point T(X, Y, Z) on the sample surface can be expressed as

$$X = -\frac{\sqrt{(a-Y)^2 + (b-Z)^2}}{\sqrt{(a-Y')^2 + (b-Z')^2}} \cdot x \tag{1}$$

$$Y = a - \frac{a}{w_j} \cdot z \tag{2}$$

$$Z = \frac{\alpha b}{\alpha + \frac{a}{w_j}} \tag{3}$$

Here, X', Y'and Z' are positions on CCD. Parameters on Eq.(1)~(3) w_j and α indicate as follows.

$$a \tan \theta_{N \cdot j} = \frac{p_j \phi_j(x, y)}{2\pi} = w_j \tag{4}$$

$$\alpha = \frac{c - y \sin \theta_0}{d + y \cos \theta_0} \tag{5}$$

Here, $\phi_j(x,y)$ gives sample's phase distribution including the height information and j means number (j=0, 1, 2...) of different periodical patterns. We can capture the intensity distribution $I_{i,j}(x, y)$ using the CCD camera when we applied the voltage like the sinusoidal wave along a time. Here, i indicates the number (i=0, 1, 2, 3) of the intensity distribution. The intensity distribution $I_{i,j}(x, y)$ can be written including the phase distribution $\phi_j(x,y)$.

$$I_{i,j}(x, y) = A(x, y) + B(x, y)\cos\left(\phi_j(x, y) + \delta_i\right) \tag{6}$$

Here, $A(x,y)$ and $B(x,y)$ are a bias component and an amplitude components, respectively. The value of phase shift δ_i give $\delta_i = (\pi/2)\times i = 0, \pi/2, \pi$ and $3\pi/2$, respectively. We have used four-step phase shifting technique to determine the phase distribution $\phi_j(x,y)$ in accordance with the number of the projected periodical pattern. Hence, we can get the phase distribution including sample's height information.

$$\phi_j(x,y) = \tan^{-1}\frac{I_{4,j}(x,y) - I_{2,j}(x,y)}{I_{1,j}(x,y) - I_{3,j}(x,y)} \tag{7}$$

From the above equations, we can determine sample's coordinates (X, Y, Z).

3. EXPERIMENT

We developed a palm-top camera for 3D profilometry as is shown in Fig.3. The size of this camera is 53mm×130mm×38mm and the weight of this camera is about 320 g. We employed a monochromatic CCD camera which has 10 bit gray scale. The focus length of the camera lens is 16mm and we can capture 73mm×95mm area. We used a laser diode with 60mW power and 650nm wavelengths. However, we adjusted the temporal output of the beam to be about 3mW from the palm-top camera. We used a resonant scanner (f = 500Hz, θ=40°) as a single MEMS mirror. In this trial, the control unit of the laser diode, the MEMS mirror and the circuit of the functional generator are set up outside the camera unit. In this measurement, we supplied the sinusoidal voltage (f = 40 kHz, E = 0~5 V) to the laser diode[5)].

Fig. 3 Palm-top camera for 3D measurement

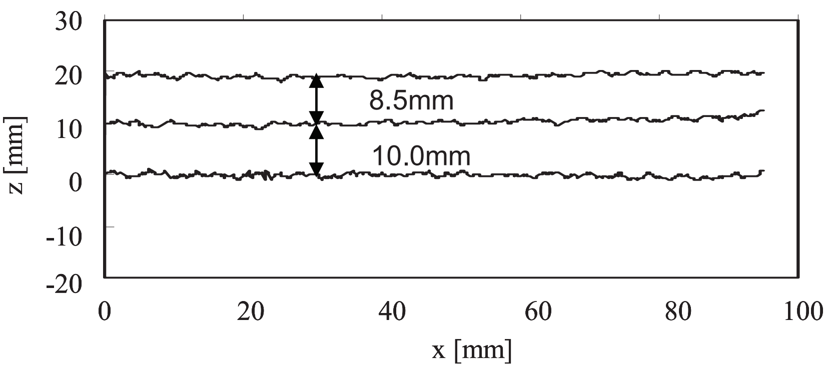
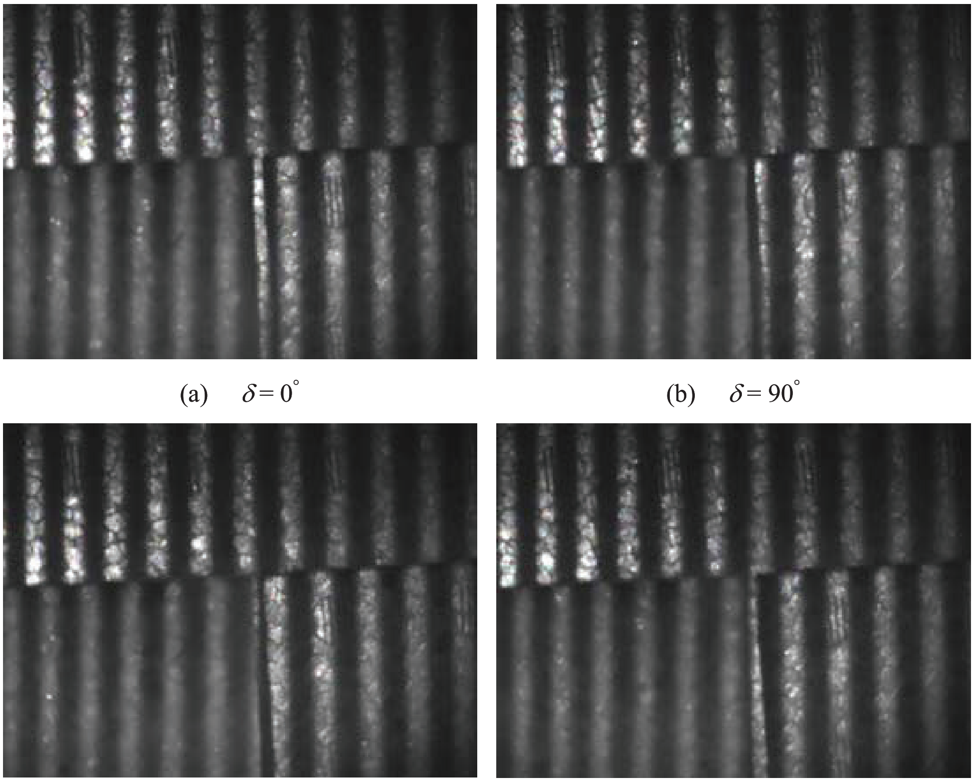


Fig.4 Performance check of test piece



(a) $\delta = 0^{\circ}$ (b) $\delta = 90^{\circ}$

(c) $\delta = 180^{\circ}$ (d) $\delta = 270^{\circ}$

Fig.5 Projected pattern of sample with small steps

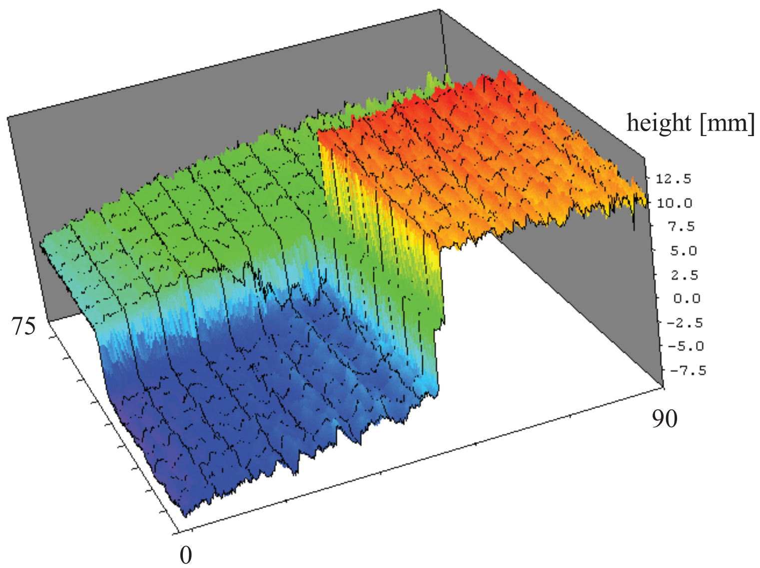
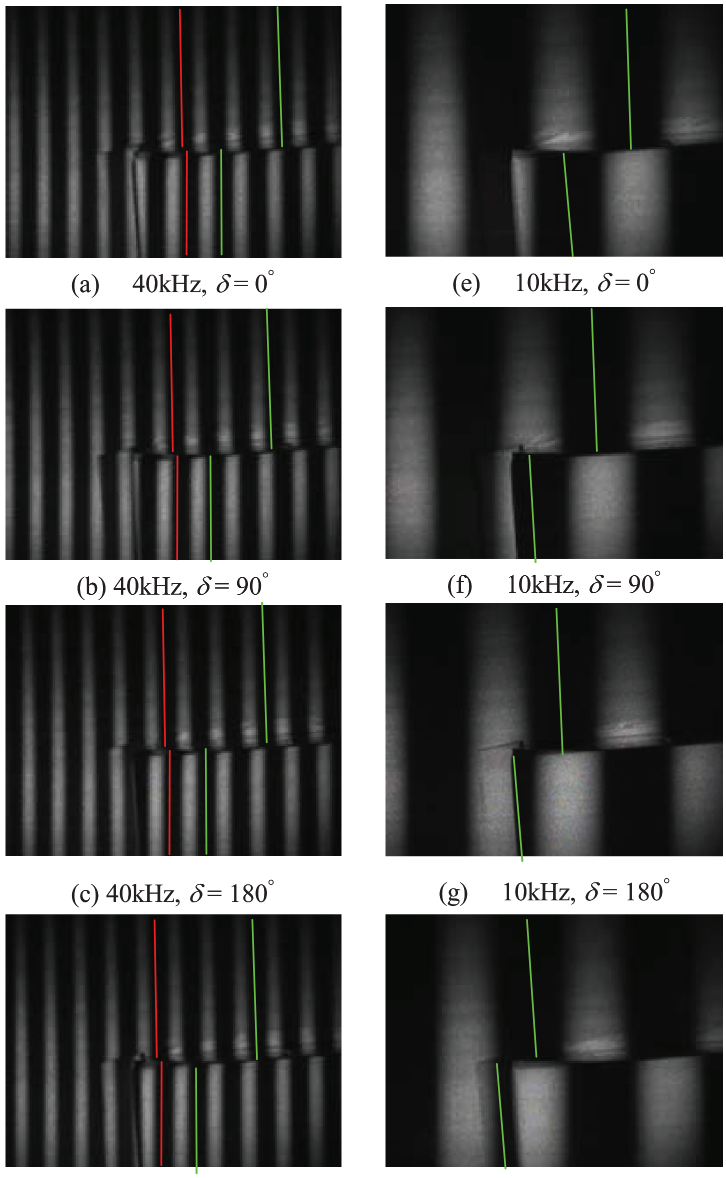


Fig.6 3D surface of the sample with different steps



(a) 40kHz, $\delta = 0^{\circ}$ (e) 10kHz, $\delta = 0^{\circ}$

(b) 40kHz, $\delta = 90^{\circ}$ (f) 10kHz, $\delta = 90^{\circ}$

(c) 40kHz, $\delta = 180^{\circ}$ (g) 10kHz, $\delta = 180^{\circ}$

(d) 40kHz, $\delta = 270^{\circ}$ (h) 10kHz, $\delta = 270^{\circ}$

Fig.7 Projected pattern on the sample with large steps using 10kHz signals

We measured the reference test pieces to check the performance of the palm-top camera as shown in Fig.4. Three test pieces were arranged like stairs. The two step heights of the stair are 10mm and 8.5mm, respectively. The accuracy of this measurement is 0.5mm according to the experiment. The very small undulations in the result were caused by the non-sinusoidal properties. To overcome undulations, we can solve this problem by adjusting the applied voltage to the laser diode and we have only to apply the sinusoidal voltage with high frequency.

We measured a sample with different steps. Each step is about 9mm and 10mm, respectively. Figure 5 shows the captured image with the different shifting phase. It is verified that our pattern projection method successfully illuminates the sample. The values of the phase shift are 0˚, 90˚, 180˚ and 270˚, respectively. Figure 6 shows three-dimensional profile of the sample. Colored level gives the height of the sample from -7.5mm to 12.5mm. This result is in good agreement with the assured value. This projected periodical pattern has been generated by a functional

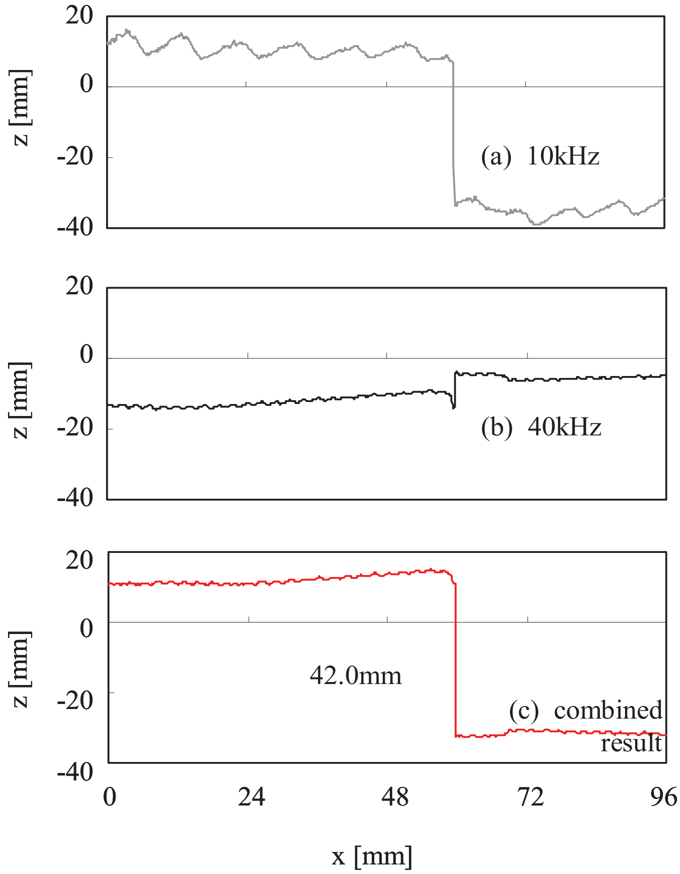


Fig.8 cross section of surface profile

generator (f = 40kHz). However this periodical pattern could not measure the height of the sample with large steps, since there is an ambiguity of the phase of the projected pattern from $-\pi$ to $+\pi$ rad.

We tried to measure a special sample with a large step (Δh=41mm). In this experiment, we illuminate two types of projection pattern. The frequencies of the signals by the functional generator are 40kHz and 10kHz, respectively. The signal with 40kHz can illuminate a narrow periodical pattern. On the other hand, the signal with 10kHz can generate a wider periodical pattern. Figure 7 shows the captured images by different projection patterns with 40kHz and 10kHz. It is difficult to identify which connection is correct such as red lines and green lines. Concerning the result as shown in Fig.7 (a)-(d), it is very clear to understand the connection of the periodical pattern from green lines shown in Fig.7 (e)-(h). According to these results, we can measure the sample with a large step by projecting a wide periodical pattern. As a matter of course, we have to project a narrow periodical pattern to measure the sample precisely.

Figure 8 shows the cross section of three-dimensional profile of the sample with a large step. The result using the signal with 10kHz can analyze three-dimensional profile as shown in Fig. 8(a). However, the result using the signal with 40kHz couldn’t analyze three-dimensional profile as shown in Fig. 8(b). The reason is an ambiguity of the phase unwrapping. On the other hand, if we take notice of the precise measurement, it is obvious that the result using the signal with 40kHz is better than the result using the signal with 10kHz. We reconstructed the profile as shown in Fig.8(c) after combing two results as shown in Fig.8(a) and Fig.8(b). According to this result, we can measure a sample with a large step using our projection method.

4. CONCLUSIONS

We have developed a palm-top camera for three dimensional profilometry and showed its versatility. The key technology to this measurement is a single MEMS mirror for digital pattern projection, not the aligned micro-mirrors as such DMD and the liquid crystal device. The camera is as small as a photographic digital camera in size. In addition, our latest improvement of measuring performance by modulating the projected pattern is demonstrated. In this experiment, we applied the signals with 10kHz and 40kHz to a laser diode. Using two different periodical patterns, we tried to measure a sample with a large step. Even in the case of a larger-stepped sample that is difficult in measurement using one periodical pattern, we successfully measured by using the combination of two different periodical patterns.

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